3-D GRMHD Simulations of Disk-Jet Coupling and Emission

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Abstract. We have performed a fully three-dimensional general relativistic magnetohydrodynamic (GRMHD) simulation of jet formation from a thin accretion disk around a Schwarzschild black hole with a free-falling corona. The initial simulation results show that a bipolar jet (velocity $\approx$ 0.3c) is created as shown by previous two-dimensional axisymmetric simulations with mirror symmetry at the equator. The 3-D simulation ran over one hundred light-crossing time units ($\tau_S = r_S/c$ where $r_S \equiv 2GM/c^2$) which is considerably longer than the previous simulations. We show that the jet is initially formed as predicted due in part to magnetic pressure from the twisting the initially uniform magnetic field and from gas pressure associated with shock formation in the region around $r = 3r_S$. At later times, the accretion disk becomes thick and the jet fades resulting in a wind that is ejected from the surface of the thickened (torus-like) disk. It should be noted that no streaming matter from a donor is included at the outer boundary in the simulation (an isolated black hole not binary black hole). The wind flows outwards with a wider angle than the initial jet. The widening of the jet is consistent with the outward moving torsional Alfvén waves (TAWs). This evolution of disk-jet coupling suggests that the jet fades with a thickened accretion disk due to the lack of streaming material from an accompanying star.

We have also calculated the free-free emission from a disk/outflow near a rotating black hole using our axisymmetric GRMHD simulation using a covariant radiative transfer formulation. Our calculation shows radiation from a shock, and hence the disk-jet coupling region is observable.

INTRODUCTION

Relativistic jets have been observed in active galactic nuclei (AGNs) [17, 2, 1], in microquasars and neutron-star X-ray binaries in our Galaxy [14, 5], and it is believed that they originate in the regions near accreting (stellar) black holes and neutron stars [11]. To investigate the dynamics of accretion disks and the associated jet formation, we have performed jet formation simulations using a full 3-D GRMHD code. This magnetic-acceleration mechanism has been proposed not only for AGN jets, but also for (nonrelativistic) protostellar jets [12], Kudoh, Matsumoto, & Shibata [11] found that

the terminal velocity of a jet is comparable to the rotational velocity of the disk at the foot of the jet in nonrelativistic MHD simulations, and that for an accreting black hole the relativistic jet should be formed in the inner disk region near the event horizon.

Koide, Shibata, & Kudoh [7, 8] have investigated in 2-D, the dynamics of an accretion disk initially threaded by a uniform magnetic field in a non-rotating corona (either in a state of steady fall or in hydrostatic equilibrium) around a non-rotating (Schwarzschild) black hole. The numerical results show that matter in the disk loses angular momentum by magnetic braking, then falls into the black hole. The disk falls faster in this simulation than in the non-relativistic case because of general-relativistic effects that are important below $3r_S$, where $r_S \equiv 2GM/c^2$ is the Schwarzschild radius. A centrifugal barrier at $r = 2r_S$ strongly decelerates the infalling material. Plasma near the shock at the centrifugal barrier is accelerated by the $\mathbf{J} \times \mathbf{B}$ force and forms bipolar jets. Inside this *magnetically driven jet*, the gradient of gas pressure also generates a jet above the shock region (*gas-pressure driven jet*). This *two-layered jet structure* is formed both in a hydrostatic corona and in a steady-state falling corona. Koide et al. [9, 10] have also developed a new GRMHD code using a Kerr geometry and have found that, with a rapidly rotating ($a \equiv J/J_{\max} = 0.95$, $J_{\max} = GM^2/c$, J and M are angular momentum and mass of black hole) black-hole magnetosphere. the maximum velocity of the jet is (0.3 - 0.4) c.

In this paper we present a fully three-dimensional, GRMHD simulation of jet formation with a thin accretion disk. Our object for this type of simulation is to determine the parameters necessary for relativistic jet formation and the resulting interaction and instabilities found between the accretion disk and the black hole. Our simulation was performed using the same parameters as in [8] in order to determine the physical differences resulting from a full 3-D versus a 2-D simulation with axisymmetry and mirror symmetry at the equator [8]. The three-dimensional simulation allows us to study the evolution of jet formation because it is run for longer light-crossing times than the previous two-dimensional simulations. We find that at the later stages of the simulation the accretion disk becomes thick and a wind is formed with a much wider angle than the collimated jet formed at the earlier stage.

SIMULATION RESULTS

We have presented the fully 3-D GRMHD simulation of a Schwarzschild black hole accretion disk system with moderate resolution [15]. Because no deliberate asymmetric perturbation was introduced, the present simulation remains largely axisymmetric. While there are some numerical difference between this simulation and our previous 2-D simulations, we confirm the presence of a two-layer jet. Moreover, the jet develops as in the 2-D simulations. Our longer simulation has allowed us to study jet evolution. At the end of this simulation the jet fades and a weak wind is generated by a thickened accretion disk. This phenomenon was not seen in our previous 2-D simulations which were run in shorter duration.

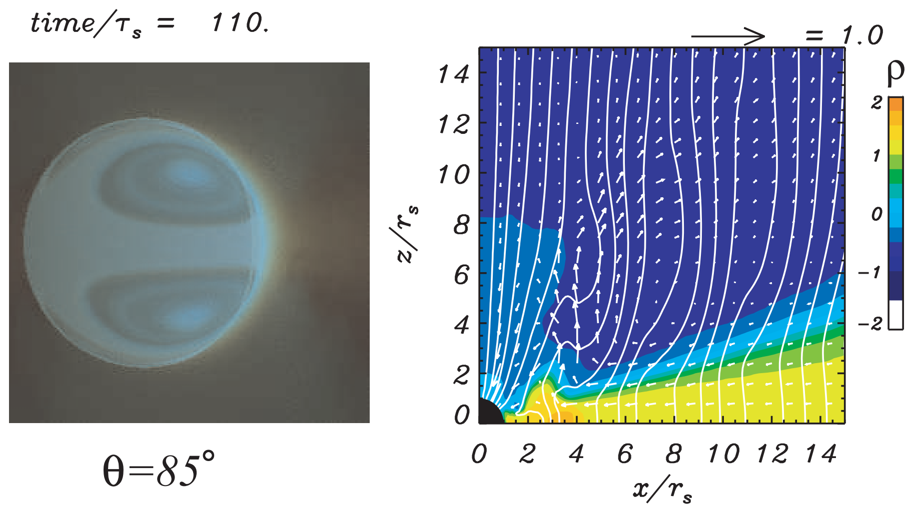

FIGURE 1. Radiation calculated based on the GRMHD simulation with Kerr metric. Right panel shows the proper density contour in color with vector potential (curves) and velocity by arrows at $t/\tau_S = 110$. The thermal radiation was calculated based on this simulation at the same time.

THERMAL EMISSION FROM DISK-JET SYSTEM

We have calculated optically thin thermal free-free emission from disk-jet system based on our 2-D GRMHD simulation. We consider a covariant radiative transfer formulation [6] and solve the transfer equation using a ray-tracing algorithm.

Figure 1 (left) shows the project image of thermal emission from the entire simulation system ($< 20r_S$) based on the simulation result at $t/\tau_s = 110$ seeing at 85 degree from the rotational axis. The right panel shows two dimensional image of a simulation results at same time (color shows the logarithmic proper density, lines represent magnetic field lines and vectors show poloidal velocity). The radiation image shows the front side of the accretion disk as well as the other side of the disk at the top and bottom regions because of the general relativistic effects. Due to the rotation of the black hole and disk, the emission from the disk moving toward us (at the left side) is enlarged. We can see the propagation of waves and the strong radiation from geometrically thick disk near the black hole. The jet generated in our GRMHD simulation is not visible in the radiation image. It is due to the fact that we have assume a thermal free-free emissivity which has a strong dependent on the density, while the jet has lower than the disk. However, the jet would be visible for process with weaker dependence on the density, such as non-thermal synchrotron process or Compton scattering.

The present paper shows the image of thermal radiation. However non-thermal radiations such as synchrotron and Compton radiation are also important mechanism in black hole - accretion disk system. If we include synchrotron radiation from simulation results. we will be able to see the strong radiation from jet components. We will address these issues in a forthcoming paper.

DISCUSSION

In this simulation at the outer boundary of the accretion disk no matter is injected, therefore after accreted matter is ejected from the accretion as a jet, the power to generate a jet is dissipated and the jet is switched to a wind. However, if streaming matter is injected at the outer boundary of accretion disk, transient changes may be controlled by accreting rates with instabilities and be related to the state transitions. Such disk-jet coupling in black hole binaries is reviewed by [4, 3]. Black hole binaries exhibit several different kinds of X-ray 'state'. The two most diametrically opposed, which illustrate the relation of jet formation to accretion, can be classified as low/hard/off and high/soft states [4, 3]. These two states provide different luminosity. Pellegrini et al. [16] have discussed a nuclear bolometric luminosity and an accretion luminosity $L_{\rm acc}$ in terms of the accretion rate $\dot{M}$ and jet power. Clearly these issues can be investigated by further 3-D GRMHD simulations, and future simulations will investigate jet formation with different states of the black hole including streaming material from an accompanying star [13] combining with radiation obtained from simulations [6].

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